NASA-CR-196405

N95-70016

(NASA-CR-196405) ATMOSPHERIC INVESTIGATION RELATED TO AEROTHERMODYNAMIC RESEARCH IN THE 90 TO 130 Km REGION BY MEANS OF TETHERED PROBES Final Report, 1 May 1988 - 30 Nov. 1990 (Smithsonian Astrophysical Observatory) 14 p

Unclas

Z9/46 0019660

Atmospheric Investigation Related to Aerothermodynamic Research in the 90 to 130 Km Region by Means of Tethered Probes

NASA Grant NAG1–876

Final Report

19660

For the period 1 May 1988 through 30 November 1990

Principal Investigator
Jack W. Slowey

April 1994

Prepared for
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

CONTENTS

ATMOSPHERIC INVESTIGATION RELATED TO AEROTHERMODYNAMIC RESEARCH IN THE 90 TO 130 KM REGION BY MEANS OF TETHERED PROBES

Final Report , NASA Grant NAG1-876

1. INTRODUCTION

The region of the earth's atmosphere between 90 and 130 km is, in general, a region of transition (and slip) flow, where the relevant Knudsen number goes through 1. At heights only slightly above 130 km, the mean-free path of reflected molecules with respect to the freestream molecules is large enough to permit the assumption of free-molecular flow and the ordinary laws of molecular gas dynamics. In other words, the gas flow in that case is typified by Knudsen numbers $\gg 1$. At heights below about 90 km, on the other hand, the applicable Knudsen numbers become $\ll 1$, and continuum flow and the classical theory of compressible fluid dynamics apply. It is in the intervening transition regions that aerodynamicists have the greatest problems, especially in regard to high Mach numbers, as in the satellite case.

The transition-flow environment as it applies to satellite orbital dynamics cannot be realistically duplicated in earth-bound laboratories. This is a matter of some concern in view of the importance of the transition region in regard to satellite reentry and similar problems involving the effects of atmospheric drag at low heights. The emergence of tether technology promises a way out of this dilemma by making it possible to utilize the atmosphere itself as a "wind tunnel" in the investigation of the transition regime. There are some very substantial problems to be overcome if this approach is to be successful, however. Not the least of these is the need to know the density and other relevant properties of the ambient atmosphere that would apply to the aerothermodynamic measurements.

Our knowledge of the earth's atmosphere above 90 km has increased enormously in the past 30 years, mostly as the result of satellite-based exploration. However, there is one region of the upper atmosphere that has only been observed by direct means in sporadic rocket flights and about which there are still many unanswered questions. That region essentially coincides with the transition-flow region between 90 and 130 km. Atmospheric physicists usually refer to it as the lower thermosphere, but for a long time it was often jokingly called the "ignorosphere"—as much a reflection of the difficulties associated with the interpretation of data from that region at the time as of the paucity of such data itself. We now have a good picture of the physical processes that affect the region, but the lack of adequate data remains. Since the lower thermosphere plays an extremely important role in the physics of the upper atmosphere, this is a concern of atmospheric science as well as aerothermodynamics.

There is a very good chance that the data that are needed by both atmospheric science and aerothermodynamics could be obtained by tethered probes deployed downward from the Shuttle or some other vehicle orbiting at greater height.

The feasibility of spaceborne tethers has been already ascertained, at the time of writing of this Final Report. In Summer 1992 a first attempt of deploying from a Shuttle Orbiter a 20 Km tether was not succesful. Because of mechanical difficulties, only 200 meter of tether were released by the Shuttle. However, three tether missions followed since Summer 1992, and all were highly succesful. These were of a tether class called SEDS (Small Expendable Deployment Systems), mounted onboard a Delta II rocket. SEDS-1 went in orbit in March 1993, an electrodynamic tether called PMG (Plasma Motor Generator) was launched in June 1993, and a SEDS-2 was orbited in March 1994. Both SEDS-1 and SEDS-2 had tethers with 20 Kilometer lenght. We do believe that enough experience has been gained with spaceborne tethers, that an atomospheric mission should be now taken again into consideration. Should the cost of a Shuttle borne atmospheric experiment of the TSS-2 class (that was studied, but never implemented) be found to be too high, we could perform an experiment using a SEDS deployer. This would reduce the cost by a factor of about 50 to 100, when compared to the cost of a TSS-2.

2. TECHNICAL DISCUSSION

The tethered satellite offers the following capabilities for use in an atmospheric mission :

- keep an instrumented payload down to a height of 125 Km, for a few days (by using an ellipical orbit, we could reach a lower perigee, at about 105 Km, for a duration of a few orbits)

- we could attach along the tether, for all its length (say, 100 Km) measurement devices (say, one every 10 Km), so that we could simultaneously measure the vertical gradients of the parameter under observation (temperature, density, etc.), as well as measure the gradients of the same parameters along the direction of motion of the system in its orbiting around the Earth. There is only the tether that makes it possible to perform these gradient measures.

- we could attach to the end of the tether a re-entry capsule, capable of performing measurements from orbital height, through the re-entry region, down to the upper atmosphere. The tether could be kept attached to the capsule (while it would be cut free at the other end), and it would act as a brake, thus reducing the temperature of the capsule to about 500 K. Once the capsule is in the atmosphere, a parachute could be deployed, and we could recover the entire package for future flights.

The potential of the tether compares favorably with other atmospheric missions already launched or under consideration, such as UARS, ISTP, and TIMED. With specific regard to TIMED, we see a tethered atmospheric mission, especially if using a SEDS, as a low-cost precursor of the more costly and more complex twin-satellite TIMED mission. A SEDS flight would generate information with a very short waiting time, and this information would arrive early enough to be of use in the design work of TIMED, taking into account the delay in development schedule that TIMED is experiencing at this time.

Among the measurements that could be carried out with the tethered atmospheric mission, there are measures of parameters that have substantial relevance in "Global Change" research. Recent studies suggest that the injection of trace gases, such as carbon dioxide and methane in the atmosphere will cause a warming in the troposphere. It has been also determined that, additionally, the increased concentration of these gases will give rise, conversely, to a greater infrared cooling in space, so that a "Greenhouse Cooling" is predicted at heights as large as the thermosphere and the ionosphere (80 to 500 Km altitude). This is the height band that the tethered satellite would probe. Since many atmospheric chemical reactions depend on temperature, as well as on the vertical structure of the atmosphere, the vertical profile of such species as NO, O, O3, H2O, OH, HO2, CO, H, and others should show a veryical readjustment. This readjustment, as well as the temperature profile could be very effectively observed with the tethered satellite, suitably equiped with sensors.

To summarize the parameters that should be measured, we prepared the following list :

1) Neutral Atmosphere

- Density
- Composition
- Temperature
- Winds
- Minor Constituent Fluxes

2) Charged-Particle Atmosphere

- Density
- Ion Composition
- Plasma Temperatures
- Winds
- Current
- Vector Magnetic Field

3) Waves and Tides

- Temporal and Spatial Gradients in the Neutral and Charged Parameters

4) Induced Environment

- Density, Composition and Temperature Perturbations
- Ionization
- Photon Production
- Gas-Surface Interactions (Scattering)
- Spacecraft Potential

It is clear that, while a single atmospheric science mission could provide data of enormous value, a number of missions will be required to provide the necessary global coverage and to fully delineate both the longer-term and the transitory effects (such as those associated with geomagnetic disturbance and wave phenomena). In this connection, some of the atmospheric science issues will require polar or near-polar orbits for their resolution, while lower-inclination orbits will be important to the resolution of others. A low-inclination orbit for the first mission(s) would be quite acceptable, with higher-inclination missions to follow. Note too that resolution of some of the issues will either require (as in the case of flux determinations) or will be very significantly enhanced by simultaneous data obtained at different heights. We do not expect—or advise—that more than a single instrumented probe be provided in the first mission(s). There is a definite need for some two- or three-probe combinations eventually, however.

We currently see no compelling need for *in situ* observations below 100 km. Admittedly, this would leave substantial gaps in the observational data base in the 80'00 km region, but the benefits of lower altitude missions do not seem sufficient to warrant an attempt to overcome the very substantial problems involved in deploying a tethered probe below the 100 km level. Assuming that adequate data are obtained at 100 km and above, it should be possible to interpolate across the remaining gaps fairly easily.

A height of 125–130 km for the first mission is acceptable. Atmosphere Explorer-C demonstrated the feasibility of making atmospheric observations at orbital velocities at a heights as low as 130 km and there no problems are anticipated in the utilization of existing instrumental techniques down to about 125 km. Valuable data, especially in regard to the ionosphere, could also be obtained at greater heights (130–150 km). In subsequent missions, it will be necessary to go to significantly lower heights. This will require some new development to overcome the complications imposed by the induced environment and this work should be initiated as soon as possible. While the ultimate goal of 100 km may not be reached until early in the next century, a height of 115 km by the year 2000 would seem to be an achievable goal for the near future.

The experimental requirements, as we see them, can be summarized as follows:

- Simultaneous measurements of most of the parameters listed in the preceding section
- Pointing control to $\pm$ 3°
- Pointing knowledge to $< \pm$ 0.1°
- Payload mass of 50–100 KG
- Power/energy of 100 watts for 5 days
- T.S. position to 100 meters
- 100 KBS TM rate
- $>$ 32 each 32 bit command words @ 1KBS
- Orbital inclination from 28° to 90° (early flights at low inclinations with subsequent evolution to polar)
- Altitudes from 135 to lowest achievable (recommend first flight at 130–125 km, decreasing at a rate of $\approx$ 5 km/flight).
- Deployment duration of 1–5 days, with near-continuous measuring.

3. CONCLUDING REMARKS

From this brief investigation, the potential of a tethered atmospheric mission emerges clearly. There is absolutely no other system that can determine the verical gradient of atmospheric properties in the "ignorosphere", with measurements performed simultaneously along the entire tether length. In addition, very low altitudes, such as 125 Km, can be probed for lengths of time that are not feasible with any other approach. There are challenges that must be addressed , such as the length of the tether (we might need 150, or even 200 Kilometer),the diameter of the tether (it might be required a diameter even smaller than the diameter of the SEDS tethers , about 0.8 mm), the design of the surface orifice to be used by an instrument such as a mass spectrometer, the energy and momentum transfers between the freestream and the surface of the tethered satellite, etc. It does not seem, however, that any of these challenges represent a "show stopper", so that the investigation of the atmospheric mission should be included by NASA in the formulation of the Agency's plans for spaceborne tethered systems.

APPENDIX A

Reprint of the paper :"THE IMPACT OF TETHERS ON ATMOSPHERIC SCIENCE", by Jack W.Slowey, presented at the Third International Conference on tethers in Space, San Francisco, CA 17-19 May 1989

22-1 NN.
89A 40179

THE IMPACT OF TETHERS ON ATMOSPHERIC SCIENCE

89-1565-CP

Jack W. Slowey
Harvard-Smithsonian Center for Astrophysics
Cambridge, Massachusetts 02138

Abstract

A program of atmospheric research that utilized tethered probes to explore the earth's lower thermosphere would have an enormous impact on atmospheric science. Such a program would resolve most of the remaining issues we have in regard to the thermosphere-ionosphere-magnetosphere system, the response of that system to solar variability, and the possible coupling of that system with lower levels of the atmosphere. It would also contribute greatly to our understanding of similar systems in the atmospheres of some of the other planets and pave the way for eventual exploration of their atmospheres by like means. This paper briefly examines several issues related to the dynamics of the lower thermosphere and discusses how *in situ* investigations by means of tethered probes could resolve them.

I. Introduction

The region of the earth's atmosphere between 90 and 130 km is one of great interest to atmospheric science. In terms of the neutral atmosphere, this region is referred to as the lower thermosphere. It is also the location of the E-region of the earth's ionosphere. It is of interest because it is the region where most of the energy that drives the atmosphere at greater heights is absorbed and because it is the primary site of the coupling that exists between the neutral and ionospheric atmospheric domains and between those domains and the earth's magnetosphere.

The primary energy source for the earth's upper atmosphere is the solar EUV radiation that is absorbed in the lower thermosphere. The heating that results from EUV absorption is, in fact, responsible for the reversal in the temperature gradient (i.e., the mesopause) that defines the transition from the mesosphere to the thermosphere and determines the temperature ultimately reached at greater heights, in what is termed the exosphere. The solar EUV varies significantly both with the 11-year solar cycle and on a day-to-day basis in connection with the solar rotation and changes in active areas on the surface of the sun. The upper atmosphere is also heated in response to corpuscular radiation from the sun and the magnitude of this can equal or exceed that of EUV for short periods of time in high latitudes. One such source of heating is particle precipitation, primarily in the dayside cusp region. Another, more important, source is the E-region ionospheric currents that are driven by the field-aligned current system connecting the ionosphere and magnetosphere. The E-region currents heat the neutral atmosphere mainly by momentum transfer (i.e., ion drag), but Joule heating probably plays a role as well. All of the energy sources resulting from corpuscular radiation vary quite dramatically in response to the changes in the solar wind that are associated with geomagnetic disturbance and the aurorae.

There is another instance of coupling between the neutral atmosphere and the ionosphere that makes this region of special interest to atmospheric science. The pressure gradients associated with thermospheric heating result in horizontal winds in this region that, among other things, have a major effect on the charged-particle motion. The neutral winds are responsible for transporting ionization to the night-time region of the atmosphere and for energy dissipation and momentum transfer by dynamo action in dragging the ions across magnetic-field lines. Coupling between the magnetosphere and ionosphere also operates in the reverse direction in that there is a very significant outflow of plasma, by several mechanisms, from the ionosphere to the magnetosphere.[1]

Thus, it can be seen that in many ways the neutral upper-atmosphere, ionosphere, and magnetosphere comprise a single system in man's near-space environment and that the main keys to a better understanding of that system are to be found in the 90-130 km region. Unfortunately, the only *in situ* observations of that region that we have come from sporadic rocket flights, which are lacking in both spatial and temporal coverage. Most of what we know about this region has, in fact, been inferred from ground-based observations of the region, which quite limited both in kind and spatial coverage, and from observations made by instrumented satellites of atmospheric conditions at considerably greater heights. That, and theoretical models of the upper atmosphere, which have now reached a high level of sophistication.

The space available here doesn't permit even a brief discussion of the historical background, but a very considerable investment has clearly been made in developing our current understanding of the 90-130 km region and its importance to the physics of the upper atmosphere. What remains now is to obtain the data that are required to finish the job. For the most part, that will require *in situ* observation on a global basis and is a task for which a tethered atmospheric probe, flown in multiple missions, appears to be uniquely qualified.

Such a program of observation, properly conducted, could resolve all of the issues still confronting atmospheric science in regard to the near-space environment. Those issues are many and we can't hope to discuss all of them here. Instead, we will focus on some of the major issues that relate to the important question of the dynamics of the lower thermosphere and show how tether-assisted *in situ* observations would act to resolve them.

10

II. Tidal structure

The EUV heating drives a complex system of thermospheric tides. At heights above 200 km, the tidal variations of the various atmospheric constituents are primarily diurnal in nature. What data we have for heights below 200 km indicates that the tides take on a pronounced semidiurnal character at lower heights, however. This is due mainly to changes in the horizontal distribution of the EUV heating as the atmosphere changes from being optically thin to being optically thick. Yet, while we understand this and other aspects of the tidal forcing fairly well, the details of the tidal structure in the lower thermosphere, where the situation is further complicated by the possible upward propagation of the mesospheric tides that result from ozone absorption,[2] are entirely a matter of conjecture at this point.

Theory and observation have been combined with coniderable success in modeling the tides at greater heights.[3] There is little doubt that this success could be extended to the lower thermosphere if the amplitudes and phases of the different tidal modes could be isolated observationally under a variety of conditions.

III. Wind Structure

The pressure gradients associated with the tides give rise to global winds and the high-latitude ionospheric convection also generates a complex pattern of winds, with magnitudes that vary considerably with the level of geomagnetic activity. The importance of these winds and the corresponding ion drifts to our understanding of the coupling between the thermosphere, ionosphere and magnetosphere and between the ionosphere and current systems closer to the earth's surface has been recognized for a long time.

Until fairly recently, observations of the neutral horizontal-wind field on anything like a global basis has been extremely limited, even at greater heights. Full-vector wind measurements were made on the Dynamics Explorer 2 spacecraft,[4] however, and these and related measurements have contributed greatly to our understanding of thermospheric dynamics and our ability to model them.[5] Similar measurements made in the lower thermosphere would, of course, be of even greater consequence.

IV. Turbulence and Mass Transport

At a short distance above the mesopause, the atmosphere undergoes a transition from turbulent mixing to diffusive separation. This transition does, of course, have a very profound effect on the structure of the atmosphere above it and there is now considerable evidence from observations at greater heights that the height of this transition region, the so-called turbopause, may be subject to variation in a variety of ways.

The problem here is that, while the distinction is obviously important to our understanding of thermospheric dynamics, it is virtually impossible to distinguish between the real changes in turbopause height that would result from changes in the eddy diffusion coefficient and the effects of vertical winds in the vicinity of the turbopause on the basis of observations made at greater heights. At heights considerably closer to the turbopause, however, there is a good chance that observations of the concentrations of a number of minor constituents having different molecular weights will permit these two effects to be separated.

V. Waves

Traveling disturbances in the ionosphere were first reported by Munro[6] over 40 years ago. Shortly after that, Martyn[7] suggested that these disturbances were associated with gravity waves in the neutral atmosphere. This idea was later developed by Hines[8] as an explanation of the ionospheric motions and other phenomena, such as the winds deduced from meteor trails. Hines gave no specific origin or origins for the waves, but suggested that they originated in the lower levels of the atmosphere. Waves that could be identified as gravity waves were first actually detected in the neutral atmosphere at heights between 286 and 510 km by density gages on the Explorer 32 satellite.[9] Subsequently, wave structures in the neutral upper atmosphere have been observed in data from a number of *in situ* experiments.

Much of the wave structure observed in the neutral upper atmosphere seems to be associated with magnetic storm activity and to originate in the auroral regions of the lower thermosphere. Gravity waves generated by the effects of magnetic disturbances in these regions are, in fact, seen as a likely mechanism by which the energy of such disturbances is transported to lower latitudes. Some of the observed medium-scale gravity waves may originate in the troposphere, however.[10,11]

There has been extensive development of the theory of gravity waves in the thermosphere since the pioneering work of Hines. We cannot give a complete account of that development, but the generation and propagation of acoustic gravity waves in the thermosphere now appears to be fairly well understood theoretically.[12,13,14] What is needed now is the opportunity to compare the theory with actual observations in and near the low-height regions where the waves presumably originate.

Concerning waves that might originate at lower heights in the atmosphere, we have only rather recently come to realize that such waves may "break" in the region of the upper mesosphere and lower thermoshere.[15,16] This would result in significant sources of mass and energy at these heights and would have a major effect on local thermospheric dynamics. It is a matter of considerable importance, therefore, to determine from observation the extent to which such gravity-wave breaking actually occurs and the effects that are produced.

References

1. Chappell, C. R., "The Terrestrial Plasma Source: A New Perspective in Solar-Terrestrial Processes from Dynamics Explorer," Rev. Geophys., **26**, 229–248, 1988.

2. Forbes, J. M., "Middle Atmospheric Tides," J. Atmos. Terr. Phys., **46**, 1049–1067, 1984.

3. Forbes, J. M., and H. B. Garrett, "Theoretical Studies of Atmospheric Tides," Rev. Geophys. Space Phys., **17**, 1951–1981, 1979.

4. Killeen, T. L., P. B. Hays, N. W. Spencer, and L. E. Warton, "Neutral Winds in the Polar Thermosphere as Measured from Dynamics Explorer," Geophys. Res. Lett., **9**, 957–960, 1982.

5. Killeen, T. L., and R. G. Roble, "Thermospheric Dynamics: Contributions From the First 5 Years of the Dynamics Explorer Program," Rev. Geophys., **26**, 329–367, 1988.

6. Munro, G.H., "Short-period Changes in the F Region of the Ionosphere," Nature, **162**, 886, 1948.

7. Martyn, D.F., "Cellular Atmospheric Waves in the Ionosphere and Troposphere," Proc. Roy. Soc. A, **201**, 216, 1950.

8. Hines, C.O., "Internal Atmospheric Gravity Waves at Ionospheric Heights," Can. J. Phys., **38**, 1441-1480, 1960.

9. Newton, G.P., D.T. Pelz, and H. Volland, "Direct in situ Measurements of Wave Propagation in the Neutral Thermosphere," J. Geophys. Res., **74**, 183-196, 1969.

10. Rice, C.J. and L.R. Sharp, "Neutral Atmospheric Waves in the Thermosphere and Tropospheric Weather Systems," Geophys. Res. Lett., **4**, 315-318, 1977.

11. Chiu, Y.T., B.C. Edgar, C.J. Rice, and L.R. Sharp, "A Correlation of Thermospheric Gravity Waves with Tropospheric Lightning," Geophys. Res. Lett., **6**, 455-458, 1979.

12. Mayr, H. G., I. Harris, F. Varosi, and F. A. Herrero, "Global Excitation of Wave Phenomena in a Dissipative Multi-Constituent Medium, 1, Transfer Function of the Earth's Thermosphere," J. Geophys. Res., **89**, 10929–10959, 1984.

13. Mayr, H. G., I. Harris, F. Varosi, and F. A. Herrero, "Global Excitation of Wave Phenomena in a Dissipative Multi-Constituent Medium, 2, Impulsive Perturbations in the Earth's Thermosphere," J. Geophys. Res., **89**, 10961–10986, 1984.

14. Mayr, H. G., I. Harris, F. Varosi, and F. A. Herrero, "Global Excitation of Wave Phenomena in a Dissipative Multi-Constituent Medium, 3, Response for Characteristics for Different Sources in the Earth's Thermosphere," J. Geophys. Res., **92**, 7657–7672, 1987.

15. Fritts, D. C., "Gravity Wave Saturation in the Middle Atmosphere: A Review of Theory and Observations," Rev. Geophys., **22**, 275–308, 1984.

16. Garcia, R. R., and S. Soloman, "The Effect of Breaking Gravity Waves on the Dynamics and Chemical Composition of the Mesosphere and Lower Thermosphere," J. Geophys. Res., **90**, 3850–3868, 1985.